Group-2 Consortium Reference Event List

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Summary

To test and validate models and path dependent correction surfaces (SSSCs) in the Group 2 Consortium's region of interest a geographically well-distributed set of reference events, located with 5 km accuracy or better, is absolutely necessary. Therefore the Consortium has launched a major effort to collect reference events in the region of interest.

We adopted a set of reference events from the CMR databases (Bondár et al., 2001) such as the nuclear explosion database (Yang et al., 2000c), ground truth database (Yang et al., 2000a) and reference event database, preciously known as calibration event bulletin (Yang et al., 2000b). These events in fact constitute the bulk of Group 2 Reference Event List. Another major source of reference events is the groomed ISC (EHB) data set (Engdahl et al., 1998). Further reference events are obtained by active search in the literature and regional bulletins as well as temporary aftershock deployments and active seismic experiments. Many events are collected by contacting local network operators. Each reference event is documented with accompanying metadata.

To facilitate bulletin search we developed two sets of selection criteria for GT5 candidate events (Bondár and Israelsson, 2001). These criteria select candidate events at 90% and 95% confidence level, respectively. GT5 candidate events are validated by cluster analysis (Engdahl and Bergman, 2001, Israelsson et al., 2001). Cluster analysis may also generate further reference events from a cluster of events.

As of July 6, 2001, there are 1,634 GT0-GT10 events in the Group 2 reference event list, 1,458 of them with arrival data (46,425 Pn, 6,161 Pg, 143,155 P, 12,935 Sn, 4,610 Lg):

- 530 nuclear explosions,
- 414 chemical explosions (calibration shots, explosions from active seismic experiments, quarry blasts and mine explosions),
- 690 earthquakes.

The distribution of events according to their GT category:

- 422 GT0 events,
- 121 GT1 events,

- 140 GT2 events,
- 889 GT5 events,
- 62 GT10 events.

The reference events are stored in an Oracle database and freely available through the Consortium’s web site, *http://g2calibration.cmr.gov*.

Introduction

The objective of the Group 2 Consortium is to develop path dependent correction surfaces (SSSCs) for the IMS stations in the Consortium’s region of interest (Fig. 1). To achieve this goal 3D models are being developed and SSSC for Pn, Pg, Sn and Lg are calculated via raytracing. To validate SSSCs reference (GT) events are relocated to demonstrate improvement on event locations when applying the corrections. Therefore it is vital importance to have a geographically evenly distributed set of reference events located with 5 km accuracy or better. In parallel with model development, the Consortium has launched a major effort to collect reference events in the region of interest. Practically all Consortium members are involved in reference event collection.

The major sources for reference events and reference event candidates are the Nuclear Explosion and Ground Truth databases maintained at the CMR (Yang et al., 2000a, Yang et al. 2000c), published locations of chemical explosions and well-located earthquakes, mine explosions and quarry blasts confirmed by local mining authorities. Candidate reference events are also selected from seismic bulletins such as the groomed ISC (EHB) data set (Engdahl et al., 1998), the CMR Reference Event Database (Yang et al., 2000b) and national and regional seismic network bulletins.

We have developed two sets of selection criteria to identify GT5 candidate events from seismic bulletins. Before acceptance, candidate reference events are validated using cluster analysis. Cluster analysis can also generate more recent reference events from a cluster (Engdahl and Bergman, 2001).

All the information is stored in an Oracle relational database. The database schema is given in a companion report (Yang, 2001). The Group 2 Reference Event List can be openly accessed at the Consortium web site, *http://g2calibration.cmr.gov* or at the Consortium's ftp server at *ftp://otto.cmr.gov/pub/group2*. A complete list of events is given in the Appendix.

In this report we provide the definition of different GT categories, give a detailed account on selection and validation of GT5 candidate events, present the station list used in Group 2 relocation studies, describe the content of the Group 2 Reference Event List and give short summary of the database representation of reference events.

Ground truth categories

Reference events are categorized according to their location accuracy and labelled as GTxx where 'xx' stands for the accuracy in location. Knowing the location accuracy of a reference event when measuring the performance of SSSCs during the relocation studies. Note that the origin time of some reference events may be poorly constrained. However, we mainly focus on the location accuracy at this time.

GT0

This category consists of events with known, accurately surveyed locations and often accurately measured origin times. These are mostly nuclear explosions with announced or published locations, calibration explosions and chemical explosions carried out during active seismic experiments. Note that chemical explosions are usually small and rarely recorded beyond near regional distances.

GT1-GT2

Events belonging to this category consist of nuclear explosions with locations obtained from space imagery or JHD analysis, mine explosions, quarry blasts and rock bursts from mines whose diameter does not exceed 2 km. Confirmation from local, national or industrial authorities is required to label an event as GT1-GT2.

GT5

Events in this category are earthquakes that pass our GT5 selection criteria and validated by cluster analysis. Promoted events from cluster analysis are also considered GT5.

GT10

In some regions where it is not possible to obtain GT5 events we revert to events located by 10 km accuracy or somewhat better. An example of this is the mid-ocean ridge and transform fault events where an event is tied to the closest bathymetry feature.

Selection and validation of candidate reference events

The GT0-GT5 event collection mainly includes chemical and nuclear explosions as well as mining events from small dimensioned mines. These events are immediately accepted as reference events if proper documentation is available. However, such data sources are rather limited both in terms of quantity and spatial distribution. Earthquakes are validated by cluster analysis. We have also developed two sets of criteria to select candidate GT5 reference events based on seismic network solutions.

In order to calibrate the IMS network, events recorded by IMS stations are desired and these arrival data are directly useful in event location calibration. Since such a requirement would limit the data available for use, in practice we collect all data and identify surrogate stations which are colocated or close to the IMS stations.

GT5 candidate selection criteria

To select candidate GT5 events from regional and global seismological bulletins we developed two sets of selection criteria, one for 90% confidence level and another for 95% confidence level. These selection criteria basically prescribe a seismic location obtained by a dense local network

GT5 selection criteria at the 90% confidence level.

- at least one station within 30 km,
- at least 10 stations within 250 km,
- maximum primary azimuthal gap <= 110 degrees for stations within 250 km,

- Pn / P phases recorded beyond 250 km.

GT5 selection criteria at the 95% confidence level.

- at least one station within 30 km,
- at least 10 stations within 250 km,
- maximum primary azimuthal gap <= 110 degrees for stations within 250 km,
- maximum secondary azimuthal gap <= 160 degrees for stations within 250 km,
- Pn / P phases recorded beyond 250 km.

Desirably for both criteria:

- observed phases at IMS or surrogate IMS stations,
- magnitude, mb >= 3.5,
- depth <= 35 km,
- event located using a local velocity model.

Secondary azimuthal gap is defined as the largest azimuthal gap a station closes. Note that events satisfying these criteria are considered candidate GT5 events. However, the location accuracy of events selected by the 90% and 95% criteria is not worse than 15 and 10 km, respectively. Selected events are validated using cluster analysis. The validation of the GT5 selection criteria is discussed in Bondár and Israelsson (2001).

Validation of candidate reference events

Candidate reference events are validated by cluster analysis. Event clusters with one or more reference events are also valuable source of reference events. Events which are not reference events initially can be “promoted” to reference events if the semi-major axis of their corresponding 90% error ellipses are less than 5.5 km. Therefore cluster analysis can generate further reference events that are typically more recent ones than the seed for the cluster. Cluster analyses also provide path-dependent station corrections which can be used for cross-validation purposes with SSSCs.

Two different methods for cluster analysis are applied, Joint Hypocenter Determination (JHD; Douglas, 1967, Dewey, 1972) and Hypocentroidal Decomposition (HDC; Engdahl and Bergman, 2000). It is important to prove that the two approaches give similar results on cluster analyses. The cross-validation of JHD and HDC methods showed that they can be used interchangeably (Engdahl et al., 2001). A detailed summary of the cluster analyses is given in Israelsson et al. (2001).

Station list

Although our mandate is to develop path dependent corrections for the IMS stations in the Group 2 Consortium region of interest, for model validation purposes it is necessary to use IMS surrogate and other non-IMS stations. During the collection of reference events we encountered several difficulties such as conflicting station codes, inaccurate or incomplete station information. As these inconsistencies may inadvertently influence locations obtained by using SSSCs, thus biasing the validation metrics, we are continually update station information and use only those stations in the relocation studies where we are confident that the site information is correct.

In Fig.1 the IMS stations for which SSSCs are developed by the Group-2 Consortium are shown as in red. Note that some station locations may somewhat differ from the CTBT station locations as the IMS network is being installed. In the Group 2 region such changes can be as large as 70 km.

Since the IMS network is not yet fully operational and data for existing IMS stations may not always be accessible, it is important to simulate the future IMS network using existing stations colocated or close to the future IMS sites. IMS surrogate stations are selected from the 75 km vicinity of an IMS site, or if there is no nearby station, the closest one. The station history is also checked for possible timing errors. If a candidate surrogate station is located in a remarkably different geological environment, the station is not accepted as a surrogate. Fig. 2 shows the map of the stations in the Consortium's region of interest.

Reference Event List 1.1

The Group-2 Consortium has initiated a major effort to collect reference events in the Group-2 Consortium region of interest. To start with, we adopted a vetted list of reference events belonging to the GT0-5 categories collected previously at the CMR. Another major source of reference events was the EHB bulletin. Further reference events are obtained by active search in the literature and regional bulletins as well as temporary aftershock deployments and active seismic experiments. Many events are collected by contacting local network operators. Each reference event are documented and accompanied with metadata.

Fig. 3 shows the distribution of reference events according to their GT category and type, such as nuclear explosions, chemical explosions and earthquakes. Fig. 4 shows the locations of the events in the Reference Event List 1.1. Of the 1634 events in the Reference Event List 1.1 1458 events have arrival data (Fig. 5). Fig. 6 shows the distribution of events as a function of the number of defining phases. Note that the majority of events have less 20 defining phases. Fig. 7 illustrates the distribution of events by the year of occurrence. Reference events are selected from the entire era of modern instrumental seismology.

The Reference Event List contains 81,425 regional rays, shown in Fig. 8, where the event to station distance is less than 20 degrees. The coverage is excellent in Europe and somewhat poorer in the Middle East and Asia. Note the almost complete lack of reference events and ray coverage in Africa. Figs. 9-12 show the Pn, Pg, Sn and Lg ray coverage maps.

Reference events collected by the CMR prior to the Group 2 effort

The Group 2 Reference Event List is compiled primarily from the CMR Ground Truth, Nuclear Explosion and Reference Event (formerly known as Calibration Event Bulletin) databases (Bondár et al., 2001). The CMR Nuclear Explosion Database (Yang et al., 2000c) contains confirmed or presumed nuclear explosions worldwide from 07/16/1945 to 5/30/1998. Arrival data for events since 1964 are obtained from the ISC/EHB bulletins. The CMR Ground Truth Database (Yang et al., 2000a) consists of chemical explosions and mining events, as well as earthquakes. Events in this database span from GT0 to GT25. The third source for events and arrival data is the Reference Event Database (Yang et al., 2000b), formerly known as Calibration Event Bulletin, since 1995. The arrival data for these events are from the REB as well as regional seismic network data. Only events belonging to GT0-GT5 categories were migrated to the Group 2 Reference Event List.

In the following the source of information is indicated by the author field in the *event* table. Nuclear explosions are indicated by a prefix of ‘EX:’.

Reference events used in previous location calibration studies in Fennoscandia

The GT events in Fennoscandia and Europe are part of the data set used for validation testing previously for the Fennoscandian SSSCs from the 1D approach (Yang et al., 2001). We migrated a subset of this data set for the Group 2 Reference Event List. During the vetting of the Fennoscandian dataset we accepted only those events that were well-documented and had an ML>2. We also tried to avoid oversampling individual mine locations.

The vetted data set contains altogether 193 events:

- CHE_NDC: an ammunition storage explosion in Switzerland on 1992/11/02.
- DEU_NDC: Teutschenthal, Germany, salt mine collapse on 1996/09/11.
- GRANT: 10 mining events in Fennoscandia during 1991/08-02/1993, Grant et al., 1993.
- ISRAELSSON: 111 mine explosions in Fennoscandia during 1995/04-1996/10.
- POL_NDC: 2 mining events in Poland on 1995/05/26 and 1995/08/25.
- SWE_NDC: 65 mine explosions in Sweden during 1995/01-1996/03.
- RUS_NDC: 3 calibration shots in the Kola Peninsula, Russian Federation during 1996/09-1997/10.

Nuclear explosions

There are 417 nuclear explosions in the region carried out by the Sovietunion, France, China, India, and Pakistan.

Soviet nuclear explosions:

- EX:AWE-JED/AWRE-JED: 92 STS and Novaya Zemlya events, Atomic Weapons Research Establishment, 1986, Atomic Weapons Establishment, 1990, Atomic Weapons Establishment, 1994.
- EX:KHRISTOFOROV: 7 Novaya Zemlya events, Khristoforov, 1996.
- EX:RICHARDS: 30 Novaya Zemlya events, Richards, 2000.
- EX:NNCKR: 97 STS events, National Nuclear Center of Kazakhstan Republic, 1999.
- EX:SULTANOV: 68 PNEs, Sultanov et al., 1999.
- EX:MURPHY+JENAB: 1 JVE event, Murphy and Jenab, 1992.
- EX:BOCHAROV: 96 other events, Bocharov et al., 1989.

Additional station readings for PNEs were made available by Harvard University.

French nuclear explosions in the Sahara:

- EX:BOLT: 13 Sahara events, Bolt, 1976., Duclaux and Michaud, 1970.

For the Sahara events additional regional data were made available by CUB.

Chinese nuclear explosions:

- EX:GUPTA+RICH: 1 Lop Nor event, Gupta and Rich, 1996.
- EX:GUPTA-JED: 9 Lop Nor events, Gupta, 1995.

EHB / ISC arrival data are associated with these explosions.

Indian and Pakistani nuclear explosions:

- EX:GUPTA+PABIAN: 1 event, Gupta and Pabian, 1996.
- EX:BARKER: 2 events, Barker et al., 1999.

EHB / ISC arrival data are associated with these explosions.

Calibration explosions, chemical explosions, and earthquakes

Calibration shots in STS and the Dead Sea:

- DTRA / DoD: 5 Balapan / Degelen calibration shots, Kazakhstan
- KAZ_NDC: 3 Balapan / Degelen calibration shots, Kazakhstan
- GII: 3 Dead Sea calibration shots, Israel, Shapira et al., 2000.

Additional regional data are included for the calibration shots in STS and the Dead Sea.

Chemical explosions carried out during active seismic experiments as well as mine explosions and quarry blasts:

- GII: 2 quarry blasts in Ramon region, Israel
- MEDIA: factory explosion in Thailand, 1999 / 09 / 19 reported by CNN
- KVAERNA: 7 chemical shots carried out during the EUROBRIDGE'95 active seismic experiment

Earthquakes:

- GII: 2 earthquakes from Golan and Gilad regions, Israel
- NORSAR: 8 Arctic Arc earthquakes, 1999 / 05-1999 / 08, NORSAR, 1999.
- THOUVENOT: Annecy earthquake, France, 1996 / 07 / 15, Thouvenot et al., 1998.

Reference events from the EHB bulletin

Candidate GT5 events in the Consortium's region of interest were selected from the EHB data set. Since the EHB events are located using primarily teleseismic phases, they were relocated by Multimax (Gupta and Wagner, 2001) using only phases recorded within 300 km. The relocated events were vetted by applying the 95% GT5 selection criteria. Of the 596 EHB GT5 candidates 448 events were accepted as GT5. As 12 events were already identified as reference events, 436 relocated EHB events entered the Reference Event List.

- EHB: 436 earthquakes relocated by using only local and regional phases within 300 km from the epicenter, Gupta and Wagner, 2001.

Reference events collected by the Group-2 Consortium

Besides events from the CMR databases and EHB bulletin, other reference events are collected independently by the Group-2 Consortium members.

Events collected by GII

- HOFSTETTER: 1 event from the Umbria-Marche aftershock sequence, Italy, Amato et al., 1998.
- HOFSTETTER: 2 events from the Adana aftershock sequence, Turkey
- HOFSTETTER: 3 events from Izmit, Turkey
- HOFSTETTER: 2 events from Düzce, Turkey

Events collected by Harvard University

- HARVARD: 35 mid-ocean ridge and transform fault events in the Gulf of Aden and the Mid-Atlantic ridge. The events are tied to the closest feature on the bathymetry map of the ridges. Since the resolution of the bathymetry map is not better than 5 km, these events are considered GT10 events.

Events collected by Multimax

- MULTIMAX: 13 events from Southern Spain between 1998-2000 from the IGN, Spain bulletin, Chan et al, 2000.

Events collected by SAIC

- EGT83: 2 chemical shots in the Ligurian Sea carried out during the EGT83 experiment, Egger et al., 1988.
- EMANOV: 3 events from Southern Siberia, Emanov et al, 1999.
- EUROBRIDGE96: 18 shots from the EUROBRIDGE'96 experiment, EUROBRIDGE Seismic Working Group, 1999.
- GIBOWICZ: 10 mine tremors from Lubin, Poland
- GIBOWICZ: 1 mine tremor from Upper Silesia, Poland
- CELEBRATION2000: 147 shots from the CELEBRATION2000 experiment, Central and Eastern Europe
- GUTERCH: 15 shots from the POLONAISE'97 experiment, Poland, Guterch et al., 1999.

- VRANCEA99: 9 shots from the VRANCEA'99 experiment, Romania
- ROCA: 2 events in the Eastern Pyreenes, Spain
- ZIVCIC: 2 aftershocks from the Krn Mountains, Slovenia

Clusters from HDC/JHD

CUB performed HDC analysis in Southeast Asia, North Africa and the Middle East (Engdahl and Bergman, 2001) and provided 268 events with 88,169 arrivals for 14 clusters. These events have location quality better than 5 km, except for the Koyna dam and Gulf of Aden events which are GT10. The starting reference events for the Aqaba, Düzce and Izmit clusters were provided by GII, reference events for the Gulf of Aden cluster were provided by Harvard University.

- ENGDAHL_HDC: 92 reference events from Balapan, Kazakhstan
- ENGDAHL_HDC: 2 reference events from Degelen, Kazakhstan
- ENGDAHL_HDC: 7 reference events and 8 promoted events from Düzce, Turkey
- ENGDAHL_HDC: 3 reference events and 3 promoted events from Erzincan, Turkey
- ENGDAHL_HDC: 3 reference events and 13 promoted events from Garm, Tajikistan
- ENGDAHL_HDC: 12 promoted events from the Gulf of Aden (GT10)
- ENGDAHL_HDC: 1 reference event and 11 promoted events in the Gulf of Aqaba, Red Sea
- ENGDAHL_HDC: 2 reference events from Hoceima, Morocco
- ENGDAHL_HDC: 1 reference event and 5 promoted events from Izmit, Turkey
- ENGDAHL_HDC: 1 reference event and 33 reference events from Jiashi, China
- ENGDAHL_HDC: 9 reference events and 6 promoted events from Koyna Dam, India (GT10)
- ENGDAHL_HDC: 4 reference events and 15 promoted events from Lop Nor, China
- ENGDAHL_HDC: 6 reference events and 13 promoted events from Racha, Georgia
- ENGDAHL_HDC: 2 reference events and 10 promoted events from Tabas, Iran

SAIC used JHD analysis for events in Europe (Israelsson, 2001) which resulted in 29 events (1,309 arrivals). The starting reference event for the Adana earthquakes was provided by GII, for the Slovenian events by Mladen Zivcic, Slovenian Geophysical Survey and for the Spanish events by Multimax and Anthony Roca, Catalonian Carthographic Institute, Barcelona, Spain.

- ISRAELSSON_JHD: 1 promoted event from Adana, Turkey
- ISRAELSSON_JHD: 9 promoted events in France
- ISRAELSSON_JHD: 9 promoted events from the Krn mountains, Slovenia
- ISRAELSSON_JHD: 10 promoted events from Spain

Events provided by the Lawrence Livermore National Laboratory, DOE

LLNL provided us a set of reference events and station readings in the Mediterranean, North Africa and the Middle East. These include:

- 18 GT0 events (already in the database)
- 32 GT15 events (events included in the CUB clusters)
- 1,294 LLNL phase picks for 104 events with unspecified accuracy in North Africa and the Middle East

Candidate reference events

There are further events we consider as candidate reference events and need to be validated.

- Eight events are selected from the Swiss Instrumental Earthquake Catalog. Although these events are classified in the catalog as having location accuracies of 2 km, they await for validation by cluster analysis.
- GT0 information on three off-shore Tunisia shots carried out during the European Geotraverse (EGT'85 Southern Segment) in 1985 (Morelli et al, 1990) are to be collected. Only the ISC bulletin for one of the shots is currently available.
- 19 evens selected from the Athen and Thessaloniki bulletins by GII. Unfortunately, none of these events meet the GT5 criteria unless further data is collected from networks in Albania and Bulgaria.
- The Italian NDC compared 80 events located by both the REB and the Italian NDC (Console, 2001). While these events may not be GT5 candidates, they are useful in comparing relocation results from using SSSCs with the two other solutions.
- HDC analysis were performed on the Cairo, 1991 aftershock sequence. However, the results cannot be accepted as reference events unless further local data is gathered.

Data availability

The reference events are publicly available through the Consortium web site *http://g2calibration.cmr.gov* or through the Consortium's ftp server *ftp://otto.cmr.gov/pub/group2*.

Database structure

The Group 2 database follows the CSS 3.0/IMS 1.0 schema. The core tables are the *affiliation, amplitude, arrival, assoc, event, netmag, origerr, origin, remark, site,* and *stamag* tables. Additional tables have also been developed for metadata, such as the *contact*, *reference, metadata, origintag* and *bibliography* tables. The extended database schema are described in a separate report (Yang, 2001). No waveform data are collected at this stage.

The Group 2 database complies with the unique identifier rule for CMR databases in general. The identifiers are obtained from the *lastid* table in the operational database. The only exception is made for the *remark* and *origin* tables for convenience, as was done in the other CMR research databases. The commid values are used to identify the GT categories of the events, for instance. commid=2 indicates that the event has a location accuracy of 2 km (GT2).

Metadata

Metadata are data about data, so they are useful in understanding and utilizing the information contained in the database. In the Reference Event List each event is validated and documented. Metadata assigned to each event is accessed through the *origintag, reference, metadata* and *bibliography* tables.

Representing measurement errors

The deltim attribute in the *arrival* table records measurement errors in arrival data. Since the arrival data are integrated from multiple data sources, the deltim values may not be consistent throughout the database. For all arrivals from the CMR databases the deltim attribute in the arrival table is consistent with the signal-to-noise ratio relation described by Israelsson et al. (1997):

- deltim = min(1.07, max(0.12, 1.07 - 1.2324*log(SNR / 3))) if there is an SNR value, or
- deltim = 0.55 if there is no SNR value, assuming SNR=7.9.

For arrival data from other sources such as the EHB database, clusters, and seismic bulletins collected by the Consortium members the deltim attribute is independent assessment of measurement errors in those data. At the absence of any deltim values in collected data, we applied the rule above for deltim values if SNR exists, otherwise we assign a default 1s (rather conservative) estimate to the measurement error.

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Group-2 Consortium region of interest

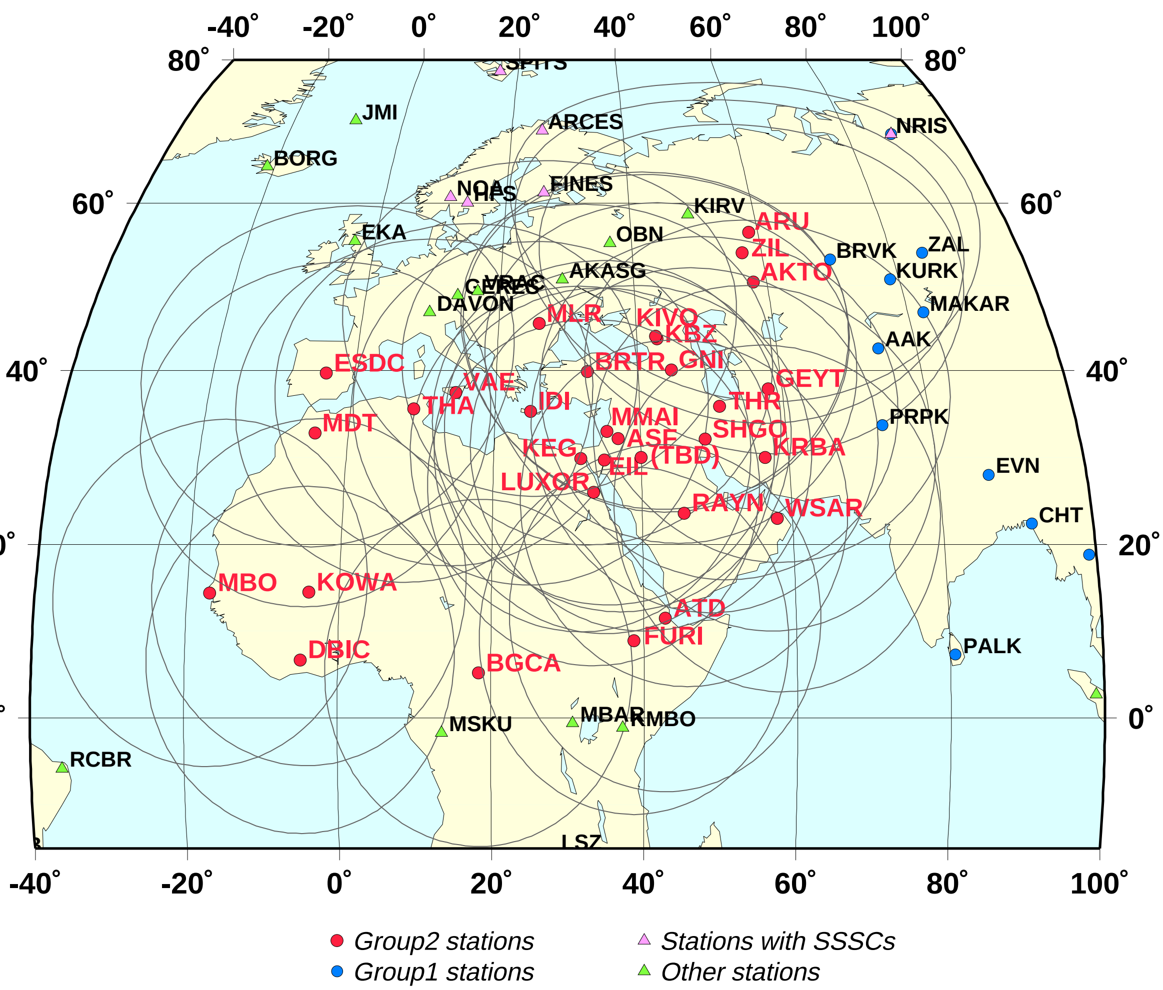

Figure 1. Group 2 Consortium region of interest. Group 2 IMS stations are shown in red.

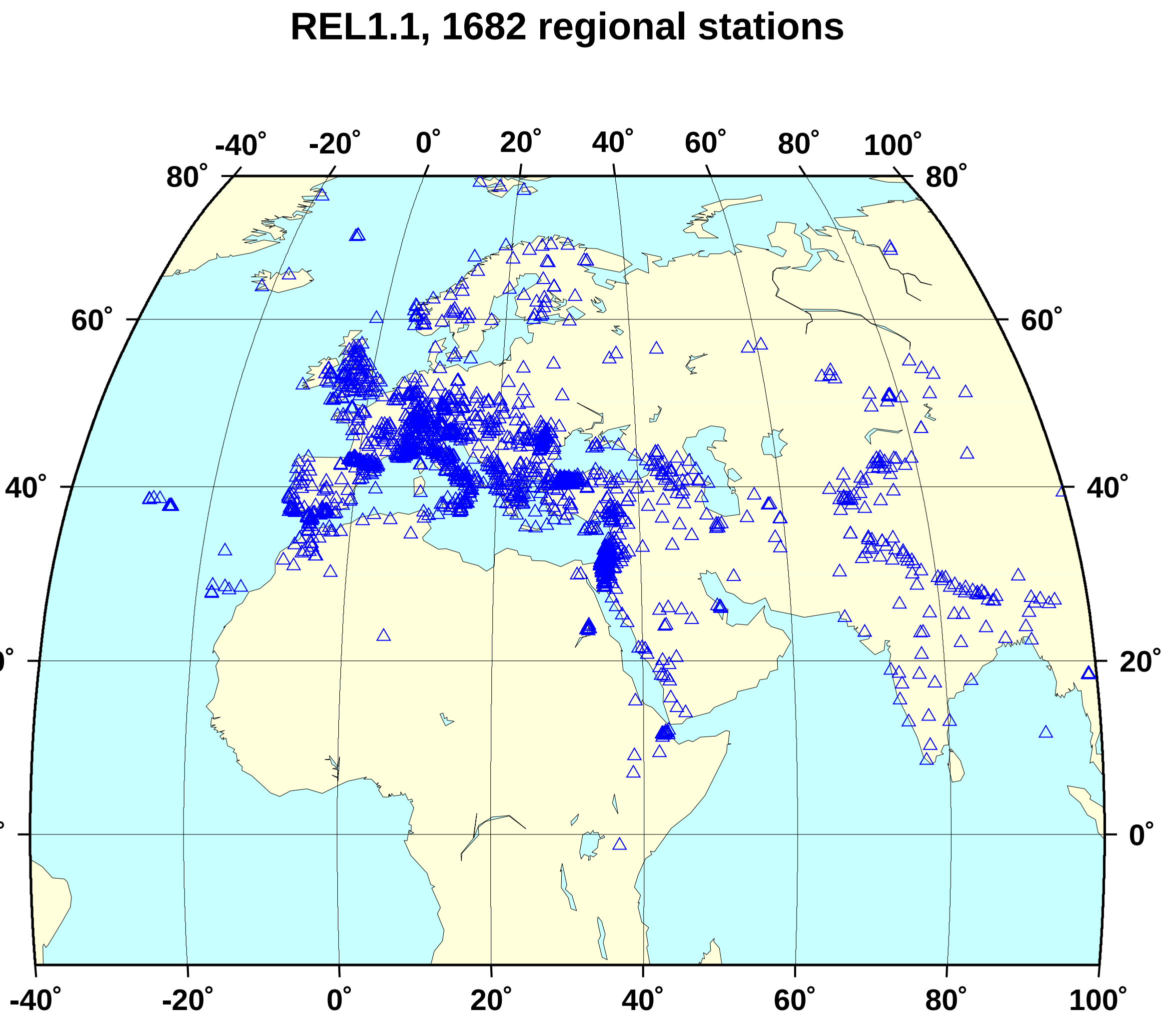

Figure 2. Stations with regional phase readings in the region of interest.

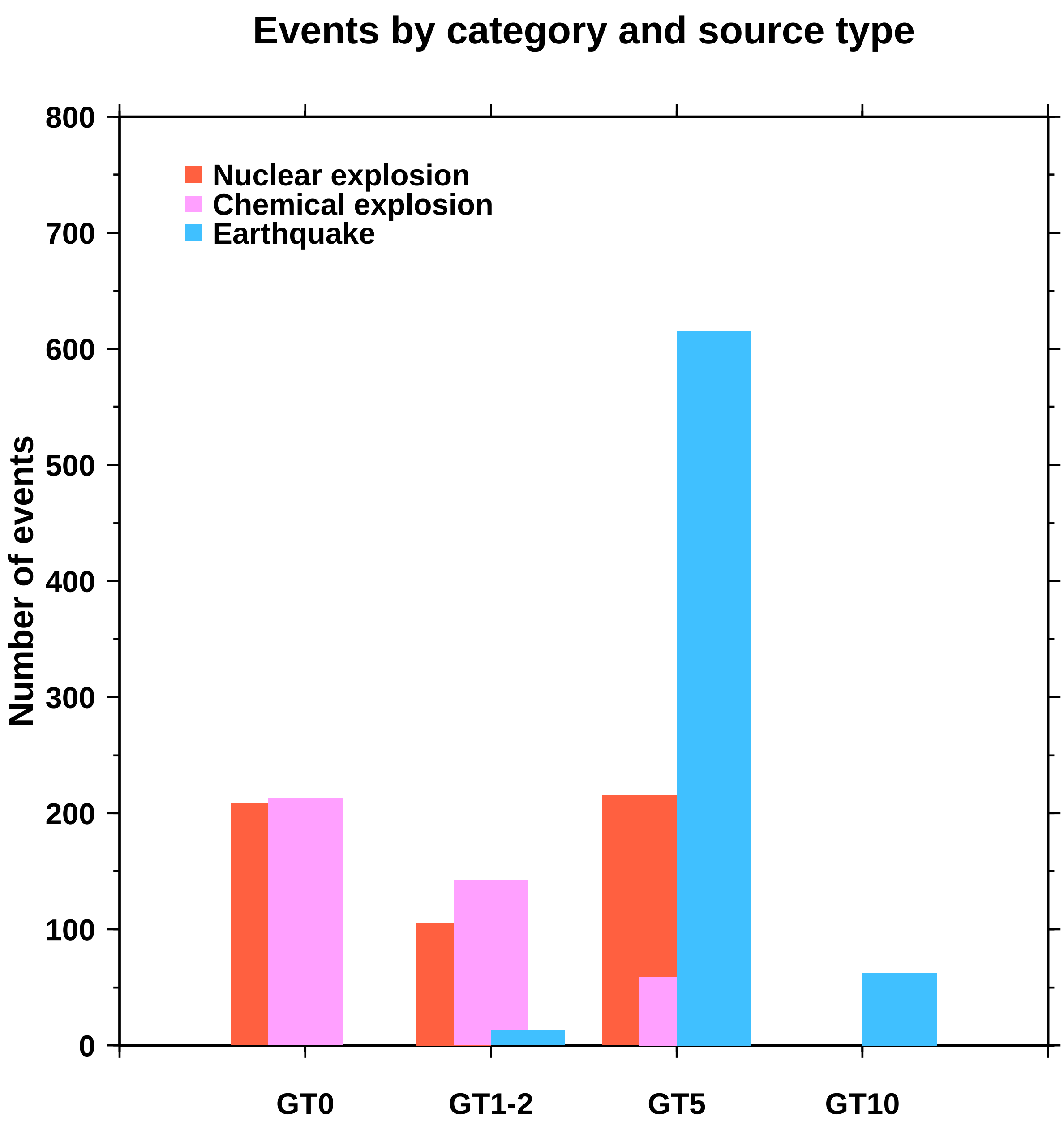

Figure 3. Distribution of reference events according to their type and accuracy.

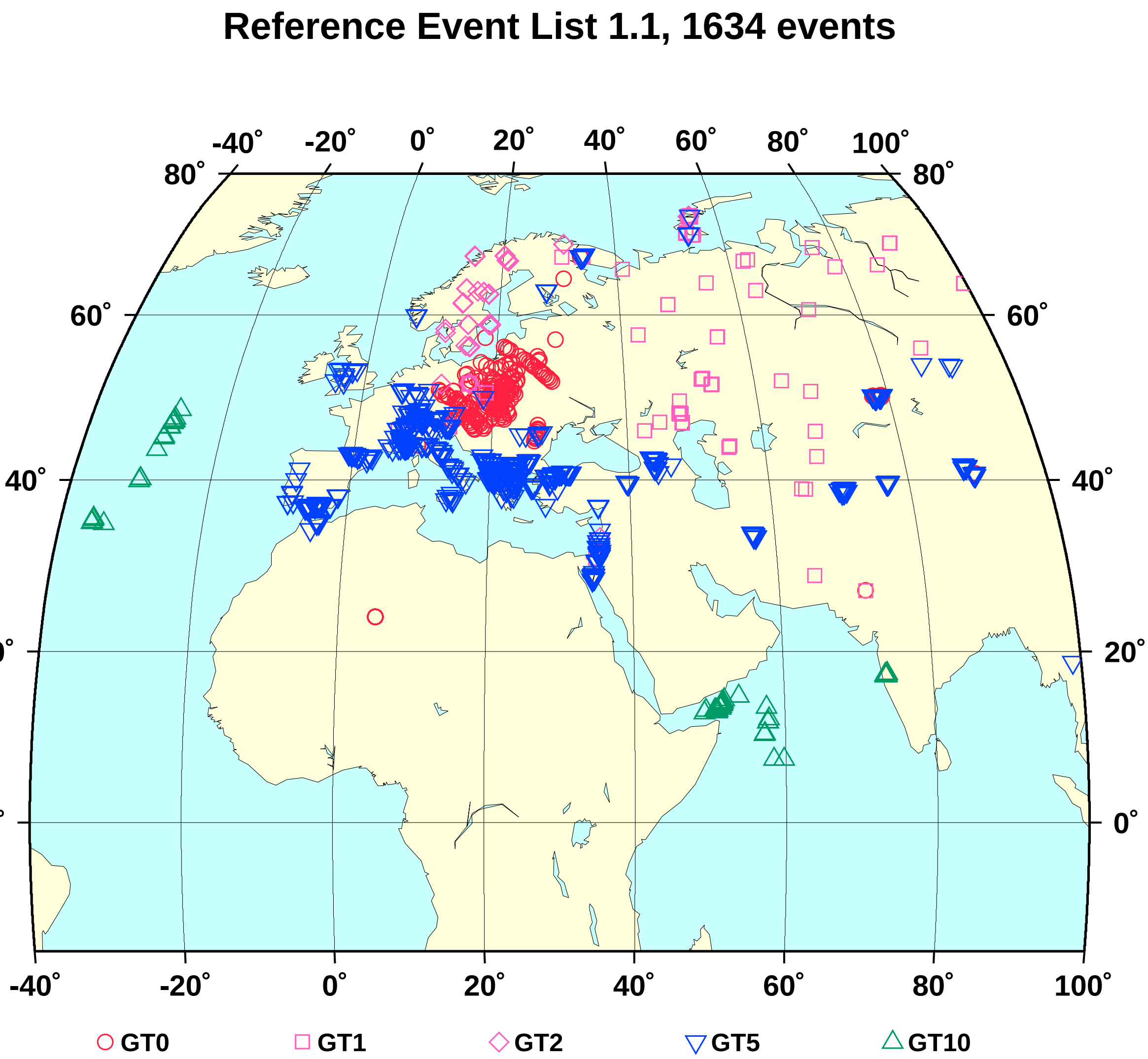

Figure 4. Geographic distribution of reference events.

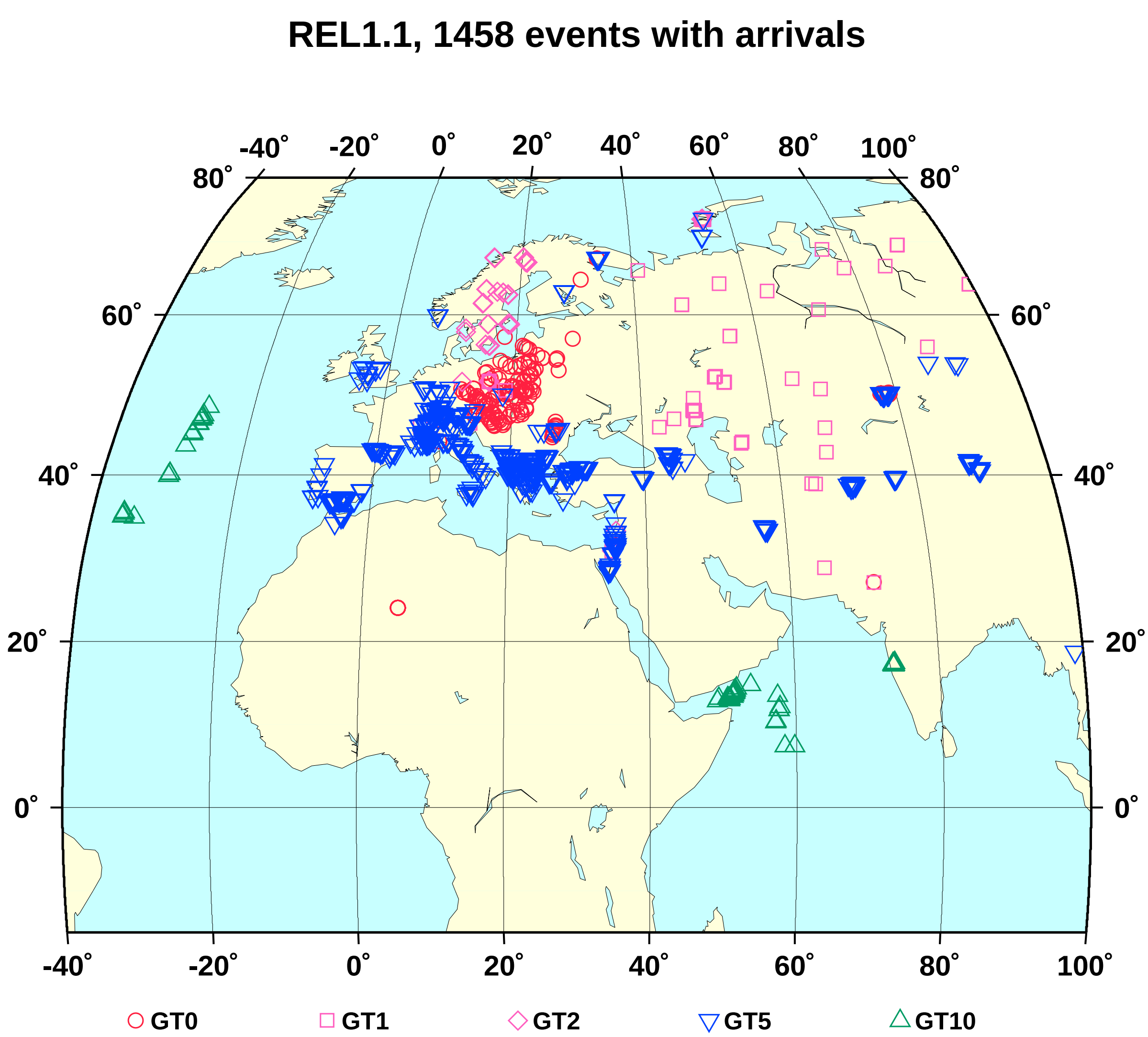

Figure 5. Reference events with arrival data.

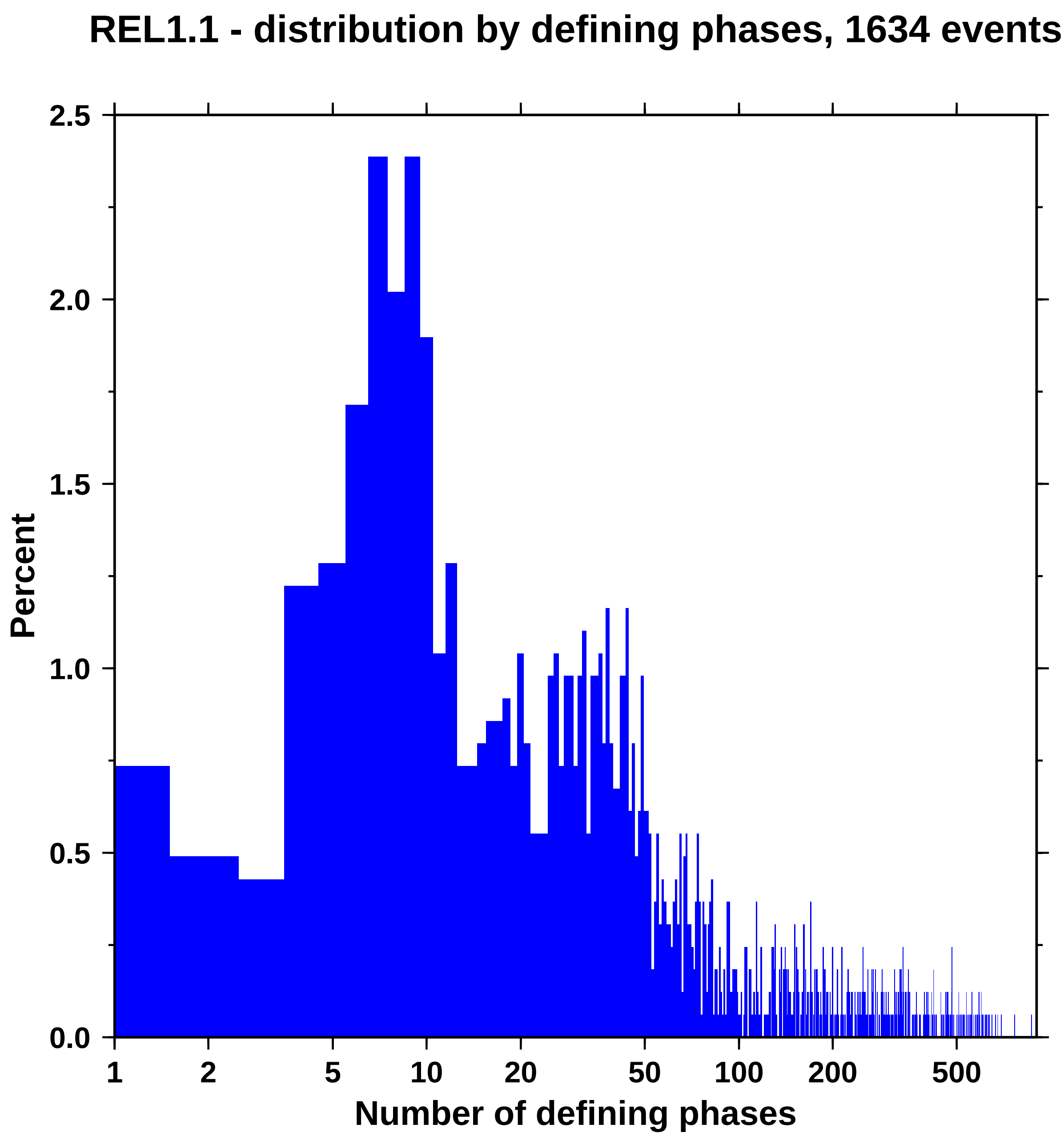

Figure 6. Distribution of events as a function of the number of defining phases.

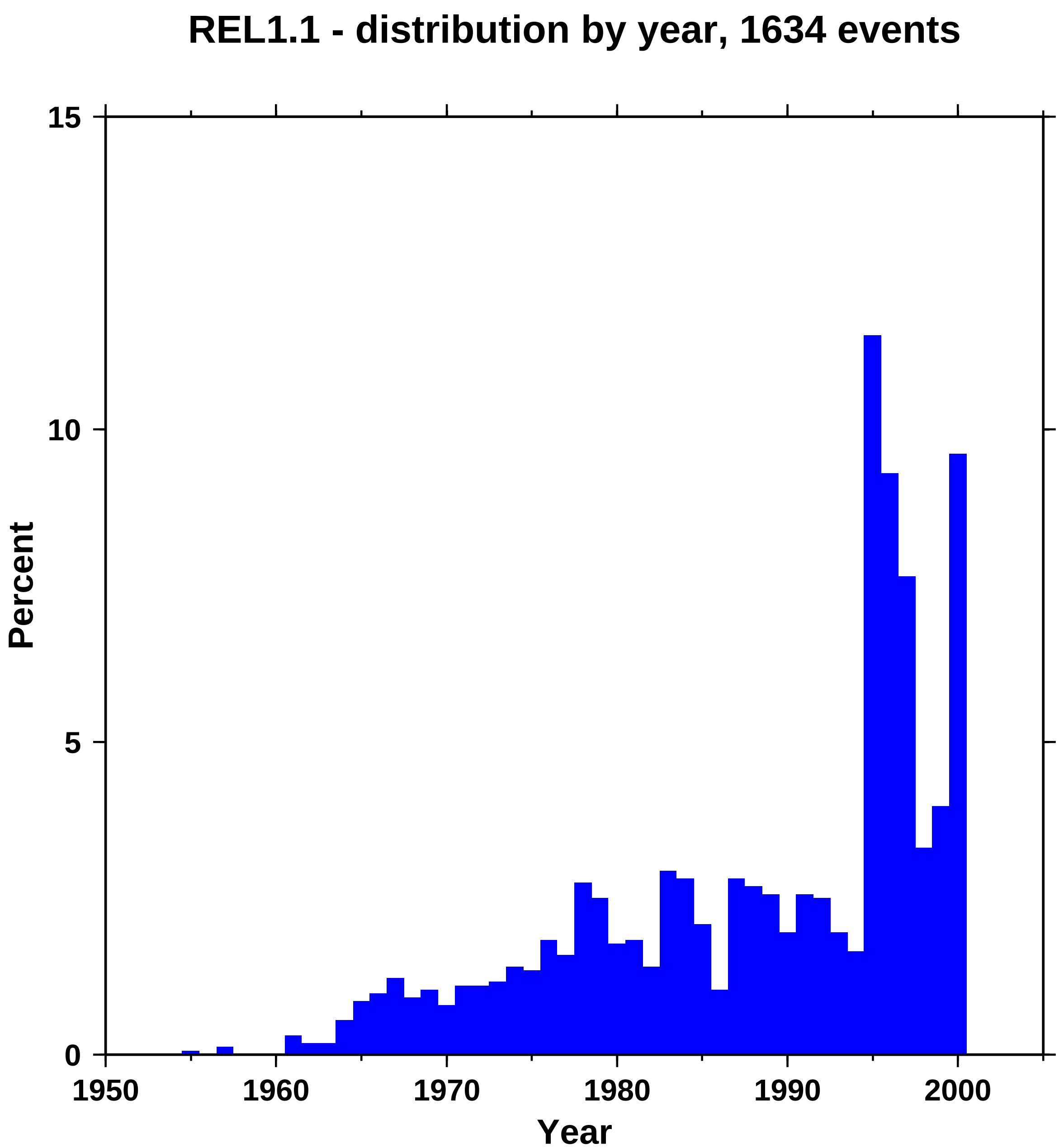

Figure 7. Distribution of events by the year of occurrence.

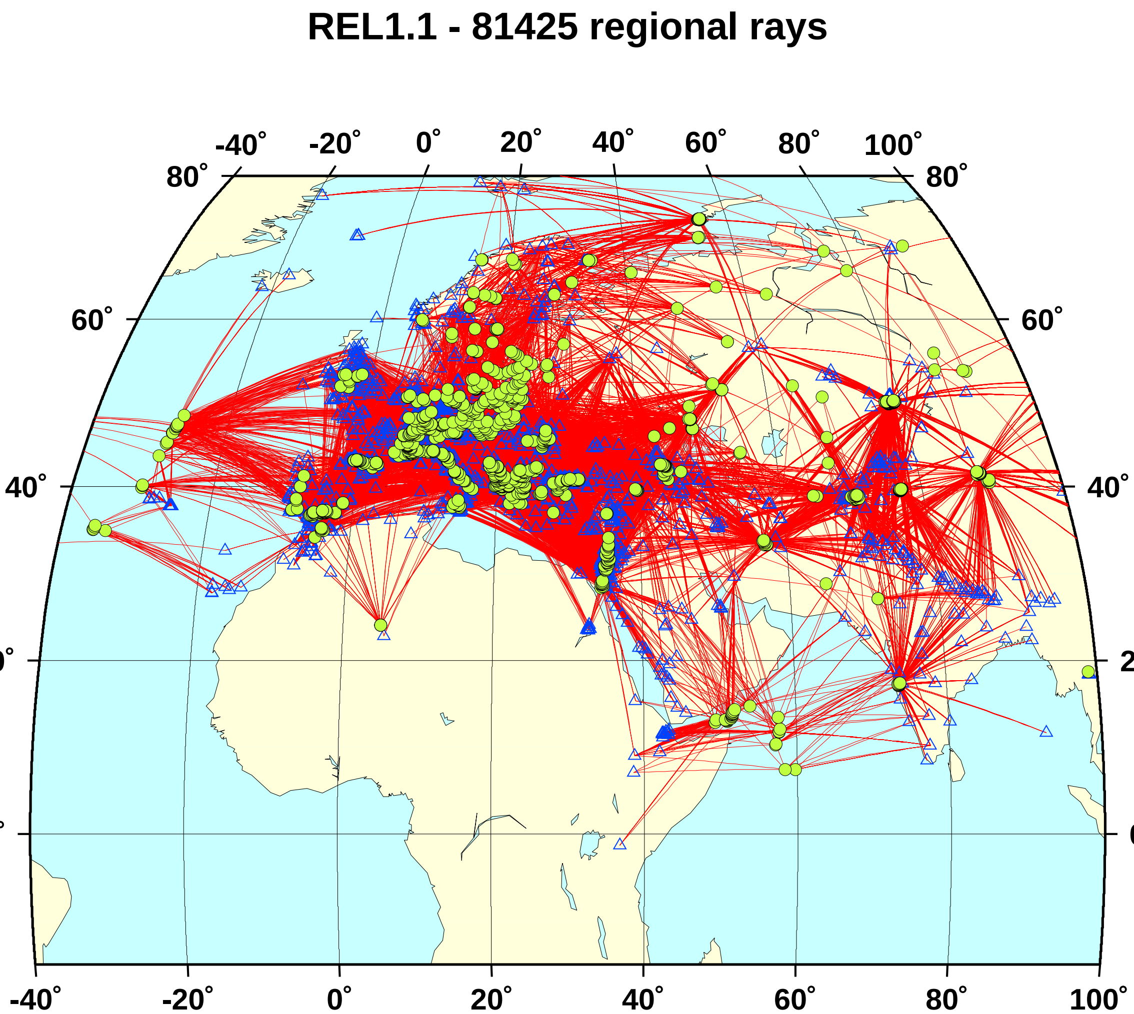

Figure 8. Regional event-station paths.

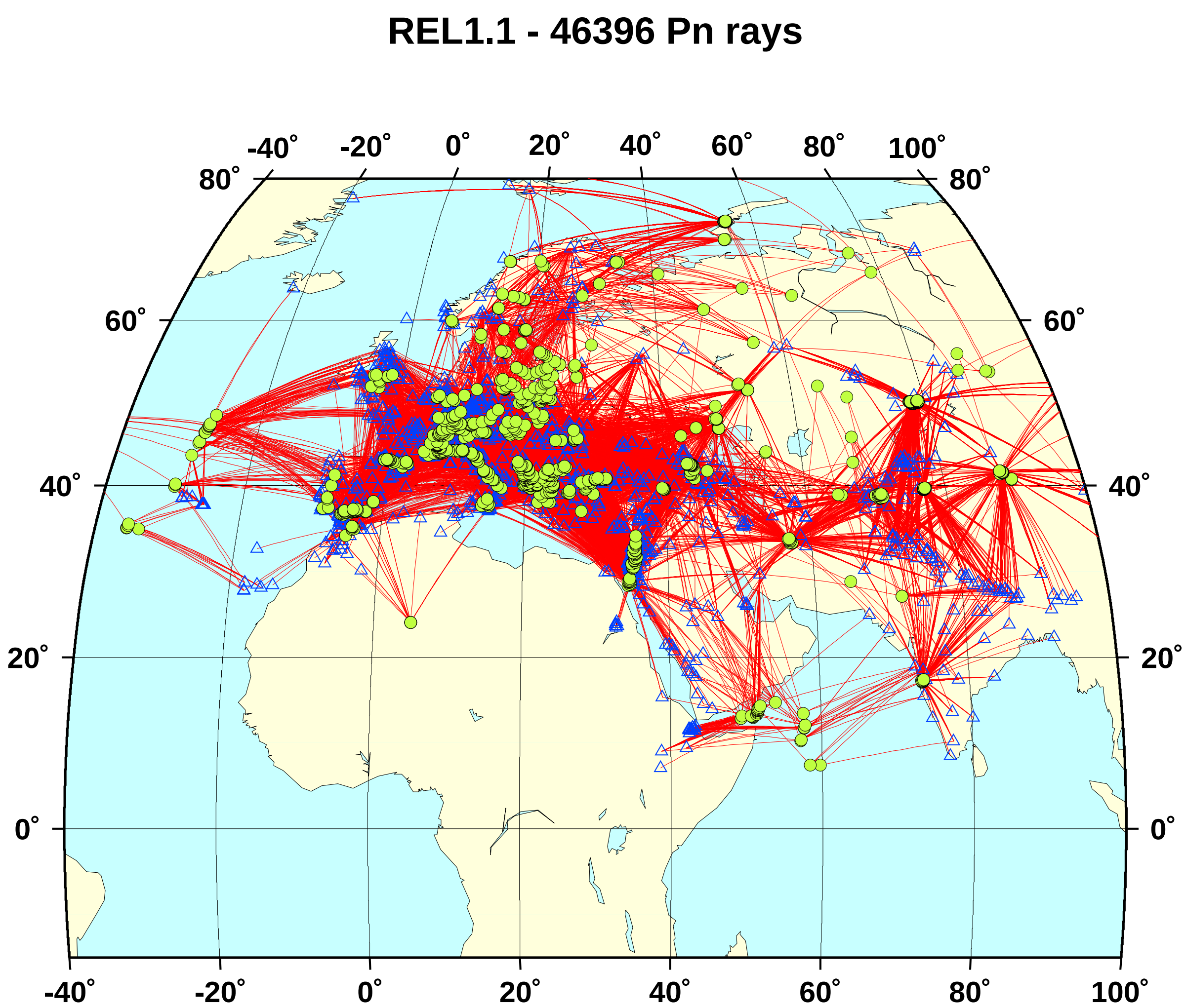

Figure 9. Event-station paths, Pn phase.

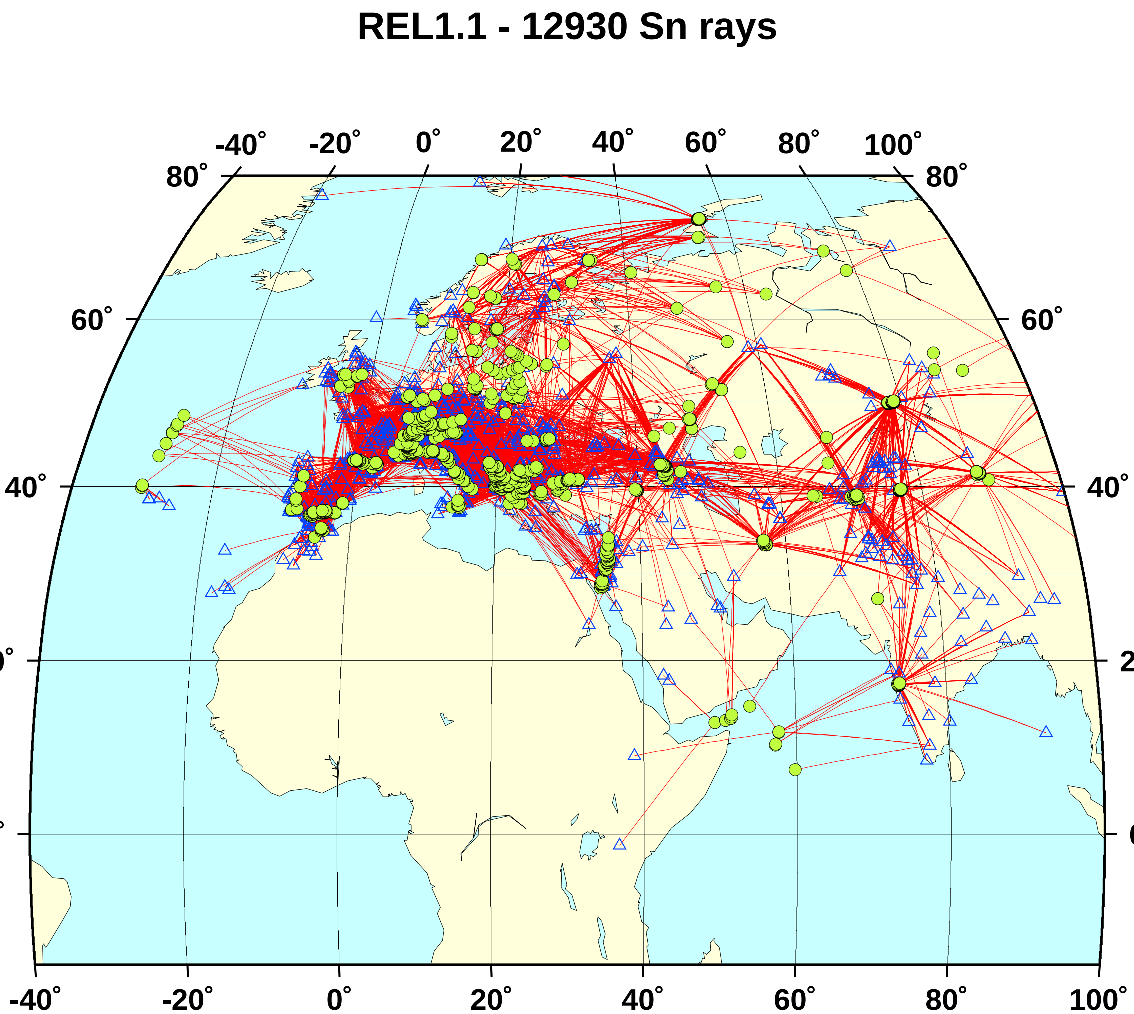

Figure 10. Event-station paths, Sn phase.

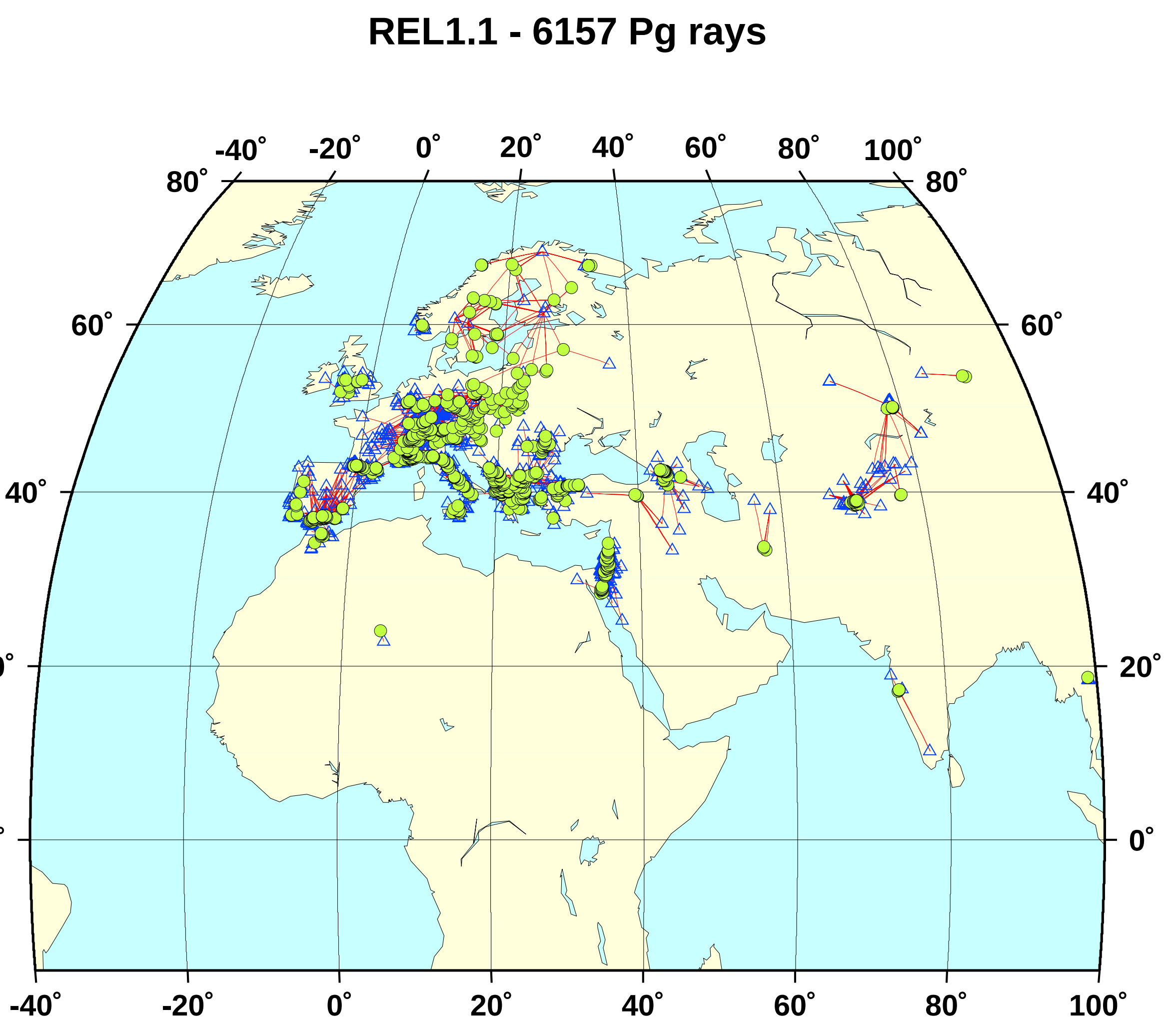

Figure 11. Event-station paths, Pg phase.

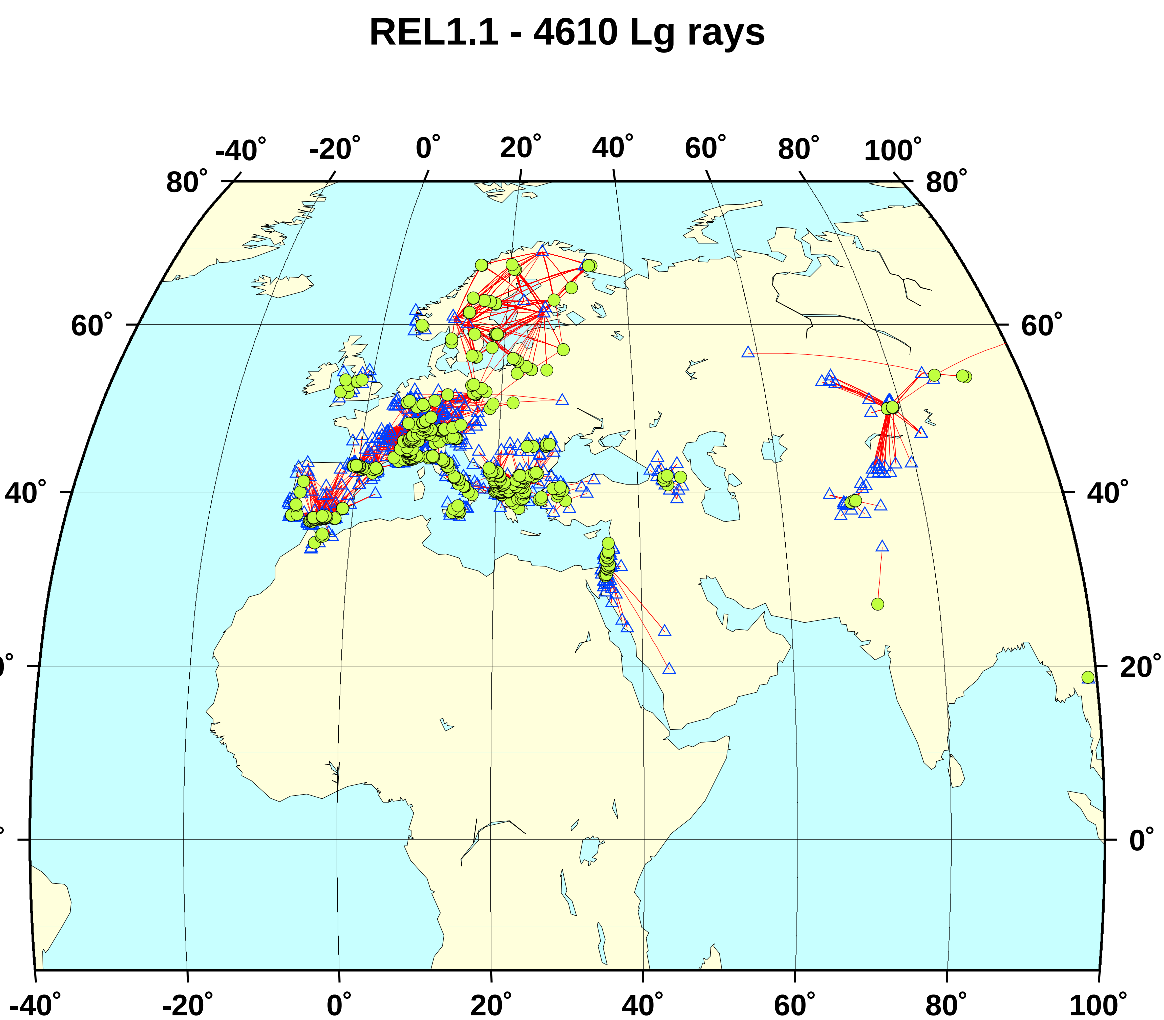

Figure 12. Event-station paths, Lg phase.